AFRL-RH-AZ-TP-2010-0001

Eye and Head Movement Characteristics in Free Visual Search of Flight-Simulator Imagery

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March 2010

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REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)* 30-11-2009	2. REPORT TYPE Technical Report	3. DATES COVERED *(From - To)* 11/22/08-11/27/09

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Eye and Head Movement Characteristics in Free Visual Search of Flight-Simulator Imagery	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **George A. Geri**	5d. PROJECT NUMBER
	5e. TASK NUMBER HA
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) L-3 Communications-Link Simulation and Training 6030 S. Kent Mesa, AZ 85212	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Human Effectiveness Directorate Warfighter Readiness Research Division 6030 South Kent Street Mesa AZ 85212-6061	10. SPONSOR/MONITOR'S ACRONYM(S) AFRL; AFRL/HEA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-HE-AZ-TR-2010-

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution A. Approved for public release; distribution unlimited. (Approval given by 88ABW/PA, 88ABW-2010-3890.)

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Free visual search (FVS) as defined here is performed while target objects are not visible, and when their possible spatial locations are not well defined. This situation is typical of real-world tasks such as air-to-ground target acquisition and search and rescue missions, but it involves gaze (i.e., combined eye and head) movements that are different from those used to perform laboratory visual search, which typically involves either clearly visible stimuli or well-defined spatial locations. In order to quantify those differences, responses were measured as observers searched for targets of both low and high conspicuity using instantaneous fields-of-view (IFOVs) of either 10º, 20º, or 40º. Gaze-saccade direction, amplitude, and duration, as well as fixation duration were obtained for the resulting gaze responses. Gaze-saccade amplitude increased from about 4º to about 7º as IFOV was increased, suggesting that no more than about 7° of the visual periphery was effectively used in the visual search. Gaze-saccade amplitude and gaze duration increased, and fixation duration decreased, with increases in target conspicuity. However, only gaze amplitude varied significantly with IFOV. A two-parameter (scale and exponent) power function was fitted to the main-sequence amplitude-duration data. Both parameters varied significantly with target conspicuity, but in opposite directions. Neither parameter varied significantly with IFOV. Quantitative differences were found between the main sequence data associated with the present FVS and those previously reported for either simple step displacements of a target or for search among known target locations. As targets were not visible during the present FVS, the data may be taken to represent the degree to which higher-level processes modify more typical gaze-saccades made to targets present in the retinal image. The present data may, therefore, be more representative of gaze responses used in real-world tasks such as air-to-ground target detection or search and rescue in which the visibility of targets may vary do to target and terrain characteristics as well as variations on lighting and atmospheric conditions.

15. SUBJECT TERMS
Eye and Head Movement, Visual Search

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Byron J. Pierce
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	UNLIMITED	31	19b. TELEPHONE NUMBER *(include area code)* 480-988-6561 x 219

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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EXECUTIVE SUMMARY

The combined eye and head movements used to perform real-world search tasks, such as air-to-ground target acquisition, monitoring target displays (e.g., radar or Forward-Looking Infrared [FLIR]), or search and rescue, are different from those used to perform search tasks typically studied in the laboratory. The main difference between free visual search (FVS) and laboratory search tasks is that FVS is performed while there is no target visible and when the spatial locations of possible targets are unknown. The situation is much different in most laboratory search tasks, which involve either flashed light stimuli or arrays of targets whose locations are clearly visible. Thus, given that eye and head movement data are difficult to obtain in the operational environment, very little such data exist in the context of FVS.

The distinction between FVS and laboratory search, as described above, is of both practical and theoretical interest—practical because laboratory findings are often applied to the operational environment, and theoretical because the relevant stimuli are different for the two types of search, and hence might be expected to differentially affect the neuromuscular mechanisms that underlie gaze responses. In order to quantify the differences between FVS and more typical laboratory search, gaze responses were measured as observers searched for targets superimposed on realistic terrain imagery presented on a large display screen. In order to determine if stimulus characteristics affected gaze-response characteristics, target conspicuity was varied by presenting either a small target (2°) on a high-detail terrain or a large target (6°) on a low-detail terrain, and instantaneous fields-of-view (IFOVs) of either 10º, 20º, or 40º were tested. Gaze-saccade direction, amplitude, and duration, as well as fixation duration were obtained for the resulting gaze responses.

Gaze-saccade amplitude increased from about 4º to about 7º as IFOV was increased, suggesting that no more than about 7° of the visual periphery was effectively used in the visual search. Gaze-saccade amplitude and gaze duration increased, and fixation duration decreased, with increases in target conspicuity. However, only gaze amplitude varied significantly with IFOV. A two-parameter (scale and exponent) power function was fitted to the main-sequence amplitude-duration data. Both parameters varied significantly with target conspicuity, but in opposite directions. Neither parameter varied significantly with IFOV. Quantitative differences were found between the main sequence data associated with the present FVS and those previously reported either for simple step displacements of a target or for search among known target locations.

As targets were not visible during the present FVS, the data may be taken to represent the degree to which higher-level processes modify more typical gaze-saccades made to targets present in the retinal image. The present data may, therefore, be more representative of gaze responses used in real-world tasks such as air-to-ground target detection or search and rescue, wherein the visibility of targets may vary do to target and terrain characteristics as well as variations on lighting and atmospheric conditions.

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1. INTRODUCTION

The eye movements associated with visual search have been studied for a variety of stimulus conditions and visual tasks [1-9]. Typically, the task involves sequential fixation of the elements of a stimulus array defined by spatial locations that are known to the observer. In addition, the relevant target stimuli are visible prior to the eye movements used to fixate them. The eye movements just described are not representative, however, of those used in many real-world search tasks in which possible target locations are not specified, and the target may not be visible until it is fixated [10-24]. Following Ford et al. [10], we will refer to tasks of this kind as free visual search (FVS). When performing FVS, and when given the opportunity to do so, observers often adopt a systematic search strategy using relatively small saccades [10,12,20,25]. FVS is characteristic of many real-world search tasks such as air-to-air target acquisition, display monitoring (e.g., radar and FLIR), and search-and-rescue. However, very limited data exist on the characteristics of either the eye or gaze (i.e., combined head and eye) movements associated with FVS.

Earlier models of saccadic eye movements had as their input a spatial error defined as the retinal distance between the fovea and the target to be fixated (e.g., [26]). However, various data indicate that consistent saccades can be made when no retinal error signal is present. For instance, it has been reported that observers can make saccades to target locations where a visible target had been extinguished [27,28], in a direction opposite to that in which the target is presented (e.g., the "antisaccade" task [29]), and even to auditory stimuli [30]. On the basis of these and related findings, more recent models of saccadic eye movements define their input in terms of higher-level (i.e., extra-retinal) mechanisms [31,32]. The higher-level mechanisms are often conceptualized simply as cognitive processes [29,33], but they have also been instantiated as spatially coded neural activity, primarily in the superior colliculus, that is used to define eye displacement (see [32] for a review).

In the present study, we have measured various characteristics of the gaze saccades associated with the FVS of imagery typically used in flight simulation. Since a visible target is generally not available in FVS, it might be expected that the characteristics of the resulting gaze movements will depend primarily on higher-level factors such as the observers' knowledge of the characteristics of the target and background stimuli (e.g., [18,34,35]). Specifically, it was expected that decreasing either target conspicuity or field-of-view would decrease gaze-saccade amplitude and increase fixation duration. Further, a comparison of the present data with those obtained using other search tasks may help to determine the extent to which higher-level processes influence search-related gaze saccades. The present data may also be useful in choosing and assessing real-world search tasks performed in military aircraft, and in designing the most appropriate methods for training those tasks.

2. METHODS

A. Observers

Seven observers were tested, and were paid for their participation. The observers had no previous experience in laboratory studies of visual search. All observers had uncorrected vision of 20/20 or better as determined by a Snellen chart.

B. Stimuli and Apparatus

The two background images are shown in Figure 1a. The desert and city backgrounds consisted of relatively low and relatively high spatial detail, respectively. The images were obtained from photographs that were digitized and then displayed using only the green channel of a cathode ray tube (CRT) projector. The background images were derived from $1024 \times 1024 \times 8$-bit images, which were displayed so as to subtend 68º on a side from a viewing distance of 1.5 m. The mean luminance of the background imagery was approximately 1.5 foot-Lamberts.

High   Low

(a) Target Conspicuity

10°   20°   40°

(b) Instantaneous Field-of-View (IFOV)
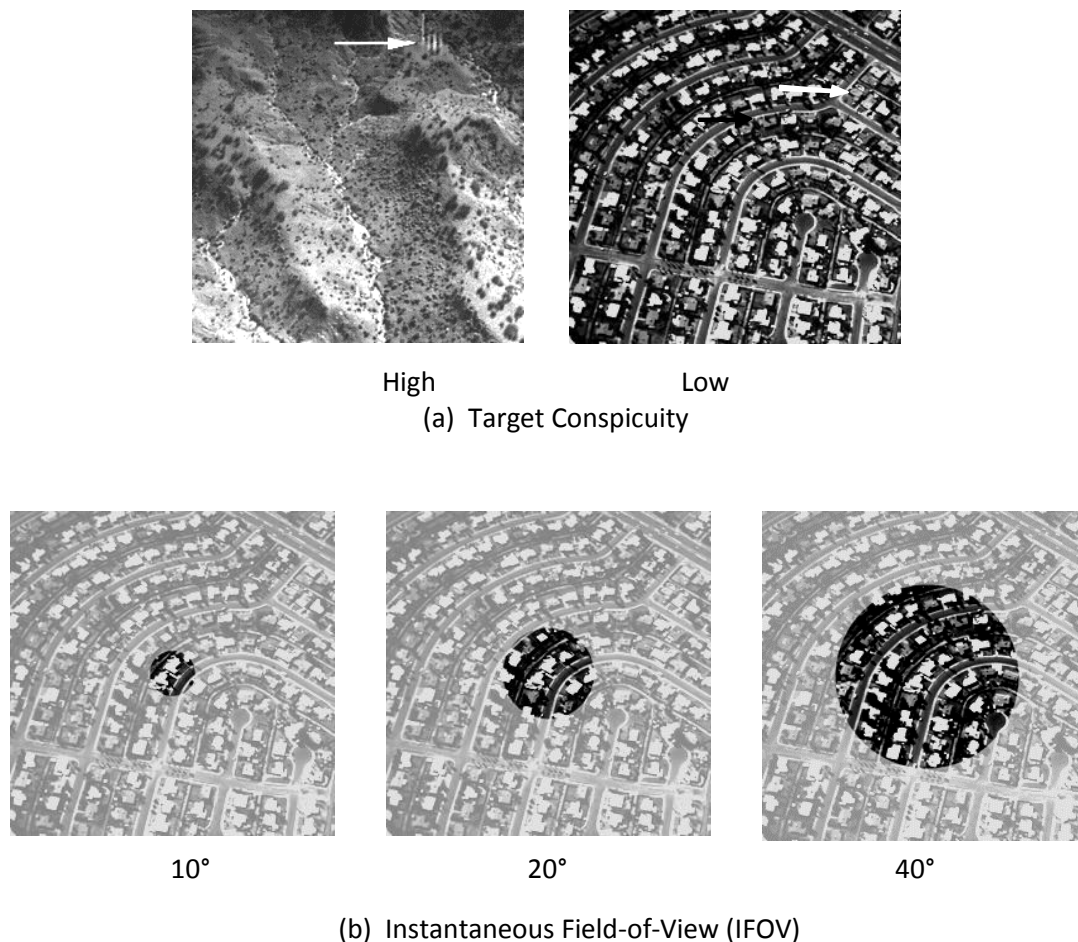
Fig. 1. (a) The target and background stimulus combinations used in the high conspicuity condition (6°-target/desert-background, shown on left) and the low conspicuity condition (2°-target/city-background, shown on right). In each case, the target is indicated by the arrow. (b) The relative sizes of the apertures providing the instantaneous fields of view of 10°, 20°, and 40°. The entire background image is shown in order to indicate the full field of view, however only the portion of the background within each aperture was visible during testing.

The test targets for the search task were cosine Gabor patches with a spatial frequency of three cycles/target measured at the half height of the Gaussian. The full test stimuli extended to $\pm 2\sigma$ of their respective Gaussian envelopes, and consisted of 32×32 and 96×96 pixels for the 2° and 6° test stimuli, respectively. Examples of the two test-target sizes as they appeared at one position within the desert background image are shown in Figure 1a. Test target contrast was varied by gradually changing the luminance (i.e., the grayscale value) of each background image pixel corresponding to the randomly chosen location of the test target. The luminance of a given pixel was varied between its original value, determined by its location in the background image, and its final value determined by its location in the target Gabor patch. The luminance of each pixel was changed so that the target reached its maximal contrast over a 15-sec interval. In addition, the time between the start of a search trial and the beginning of the target-onset interval was varied randomly between 0 and 5 sec.

Two combinations of target size and background detail were used in the present study. The combinations were 6°-target/desert-background and 2°-target/city-background, and are referred to as the *high conspicuity* and *low conspicuity* conditions, respectively.

The observers' instantaneous field-of-view (IFOV) was determined by apertures placed approximately 1.5 inches in front of each eye and centered on each pupil. The aperture views were fused by the observers, giving the visual impression of a single aperture, of either 10°, 20°, or 40°, centered on the observers' line-of-sight. The relative extent of the background images viewed through the three apertures is shown in Figure 1b. All stimuli were displayed on a rear-projection screen using a Barco Model 801 CRT projector. The background imagery was displayed and the test stimuli were controlled by a SGI Indigo Elan workstation.

Head movements were measured in two-dimensions (pitch and yaw) using a Polhemus 3Space FASTRAK system. Changes in roll angle and three-dimensional head translation were found to be insignificant in the present experimental context. Eye movements were measured using an El-Mar Series 2000 eye tracking system. Head- and eye-movements were sampled at 120 Hz and all data collection was controlled by a PC. Head data were acquired through the PC serial port while eye position data were acquired through two 12-bit A/D channels (Data Translation DT-2801A). All data acquisition was synchronized to the head tracking system. Special-purpose software was used for both real-time display of eye and gaze (i.e., combined head and eye) position, and for off-line data analysis (see Section D).

C. Procedure

The observers acclimated to the ambient light level of the experimental room by viewing one background image for 8-10 min while the head- and eye-movement systems were calibrated. The observers were then shown the test target for which they would be searching. They were informed that the target would initially be invisible and would then increase gradually in contrast until they indicated detection by pressing a mouse button. The observers were also informed that the target could appear anywhere within the background image. Each trial began when the observer was asked to begin searching for the test target.

All three IFOVs for both levels of target conspicuity were tested in each experimental session. The order in which the conditions were tested was randomized for each observer. For each condition in a given session, the observers searched for the test stimulus in ten separate trials that lasted until either the test stimulus was detected or the allotted 35 sec search time was exceeded. Each experimental session, including observer acclimation and equipment calibration,

lasted about 45 min. All observers rested for 5-8 min after four conditions were run, and in addition they were allowed to rest as required between the other conditions.

Horizontal and vertical head and eye movements were recorded at a sampling rate of 120 Hz throughout each 15-35 sec experimental trial. Data collection was automatically terminated after 35 sec, although observers were allowed to continue their search until the target was detected.

D. Analysis of Head and Eye Movement Data

Horizontal and vertical gaze records were generated as a vector sum of the recorded head and eye movements. Data were collected as the observers scanned the visual display using relatively slow (<35°/sec) head movements. Under these conditions, compensatory eye movements were very accurate and no significant differences between the saccadic eye movements and their representation in the gaze record (see Figure 3) could be detected. Therefore, the analysis of saccades was restricted to the gaze record and those responses are referred to as 'gaze saccades'.

Gaze saccades in the individual horizontal and vertical records were identified and analyzed based on direction, velocity, and duration of movement. To qualify as the onset of a gaze saccade, the response for three successive sample points had to be in the same direction, and the change between each pair of successive points had to be at least 0.05°. The velocity at each sample point, n, in the full record was found by measuring the average displacement of samples $n-3$ and $n+3$ and dividing that average by the time between those two samples. When the estimated velocity of a sequentially measured sample increased to 15 °/sec, the previous sample was taken as the start of the saccade. Likewise, when the estimated velocity of a sample dropped below 15 °/sec, it was taken as the end of the saccade.

Gaze-saccade components identified in the horizontal and vertical records, as described above, were further analyzed to determine if they belonged to a pair and thus were part of a saccade that was not purely horizontal or vertical. The components were paired as follows. The gaze-saccade components in both the horizontal or vertical records were scanned in order to find the one that occurred first. The next component in the other record was then paired with it only if their onset times differed by less than 50 msec and their durations differed by less than 40 msec. If the components identified in the horizontal and vertical records had no correlate in the other record, they were taken to be purely horizontal or purely vertical gaze saccades. A visual inspection of the response records indicated that fixation durations, as identified by our software, that were outside of this range were associated with noise or response artifacts.

Any group of points that met both the displacement and velocity criteria was then identified as a component of a gaze saccade if its duration was between 17 and 180 msec, its average velocity was between 40 and 400 deg/sec, and its amplitude was greater than 0.4°. In addition, fixation durations less than 83 msec and greater than 1500 msec were excluded from further analysis.

Main-sequence analysis has proven to be a useful technique for comparing the basic properties of various head- and eye-movement responses. Among the response characteristics typically compared are amplitude, duration, and peak velocity. The 120-Hz sampling rate used here would have been only marginally suitable for estimating peak velocity. Therefore, only the

main sequence relating amplitude and duration was considered. For this purpose, a power function of the form:

$$Duration = a \cdot (Amplitude)^b \qquad (1)$$

was fitted to the data relating gaze-saccade amplitude and duration. The scaling parameter, *a*, and the exponent, *b*, were estimated using nonlinear regression [36].

3. RESULTS

A. Head, Eye, and Gaze Movements

Shown in Figure 2 are head (solid lines) and gaze (dotted lines) movements plotted over the 2-D spatial coordinates of the test image. The data shown are for the low-conspicuity / 20° IFOV condition, but they are typical of all conditions tested. All observers displayed a systematic pattern of head and gaze movements, although there were differences in the specific patterns used. For at least five of the observers (i.e., excluding KL and MC) the gaze-scan pattern was sufficiently consistent to estimate the spacing of the horizontal and/or vertical components of the scans. For these observers, the scan spacing varied from about 6°-12° with a mean of about 8°.
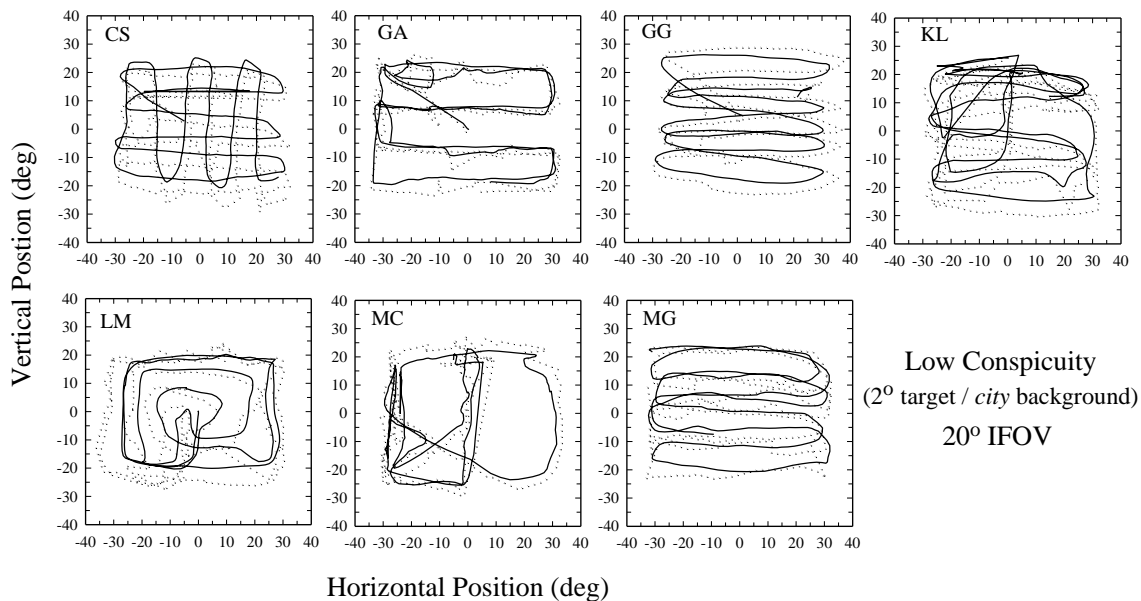
Fig. 2. Typical head (solid lines) and gaze (head+eye) (dotted lines) scanning patterns for each of the seven observers tested under the low-conspicuity/20°-IFOV condition.

Typical head, eye, and gaze plotted over time are shown in Figure 3 for observer GG and the three IFOV conditions. For IFOV=10°, the eye record is relatively flat, indicating that the eyes remained well centered relative to the head as the test image was viewed. As a result, the head and gaze records are very well matched. For IFOV=20° and IFOV=40°, the eye record
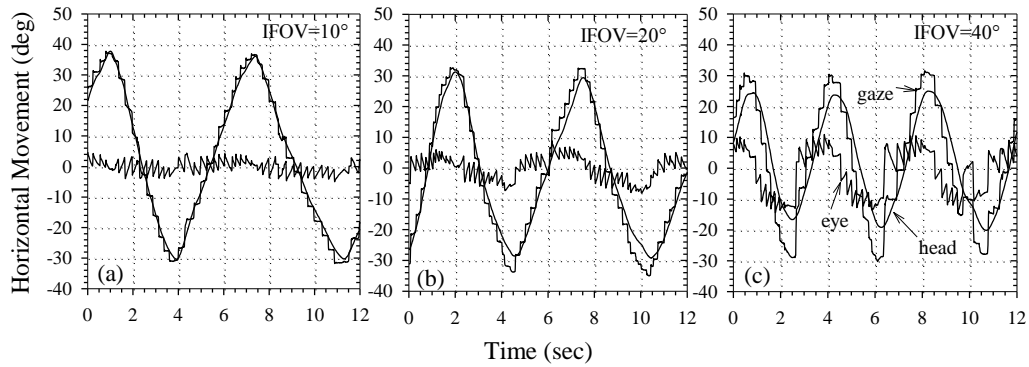
Fig. 3. Typical head, eye, and gaze (head+eye) recordings for a portion of one trial for observer GG. The data shown are for all three IFOVs under the low-conspicuity condition. The eye record deviates more from the zero position (i.e., eye centered in head) as IFOV increases.

deviates about the zero position indicating that the eye was decentered relative to the head. More specifically, the eye maintained a decentered position in the direction of the scan. Maximum decentering occurred near the center of each leftward and rightward scan, and minimum decentering occurred where the scan direction was changing. The amount of decentering for the IFOV=20° (see Figure 2) and IFOV=40° conditions was about 6° and 10°, respectively.

B. Gaze-Saccade Amplitude and Duration

Shown in Figure 4 are gaze-saccade amplitude histograms obtained from observer MG for each of the conspicuity / IFOV conditions. The histograms include all saccades identified in the ten trials run under each experimental condition for that observer. The histograms, which are typical of all observers tested, peak at higher gaze amplitudes and become wider for both the higher target conspicuity and for the higher IFOVs. The low-amplitude sub-peaks in the histograms of Figure 4 represent, for the most part, saccades that were made when gaze-scan direction was changing. Gaze-saccade amplitudes averaged over all seven observers for each experimental condition are shown by the black-bar graphs of Figure 5. Mean gaze-saccade amplitude was 5.7° for the low conspicuity condition, and 6.0° for the high conspicuity condition. This difference just reached statistical significance ($F(1,6)=6.0$, $p=0.05$). Mean gaze-saccade amplitude was 4.6°, 5.8°, and 7.3° for the 10°, 20°, and 40° IFOVs, respectively. The change in gaze-saccade amplitude with IFOV was also statistically significant ($F(2,12)=70$, $p< 0.001$).

Gaze-saccade durations averaged for the seven observers for each experimental condition are shown by the crosshatched-bar graphs of Figure 5. Mean gaze-saccade duration was 57.2 msec for the low conspicuity condition, and 59.0 msec for the high conspicuity condition. This difference was statistically significant ($F(1,6)=5.7$, $p=0.05$). Mean gaze-saccade durations were 55.2 msec, 58.6 msec, and 60.6 msec for the 10°, 20°, and 40° IFOVs, respectively. The change in gaze-saccade duration with IFOV was statistically significant ($F(2,12)=7.1$, $p< 0.03$).

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C. Fixation Duration

Fixation duration averaged for the seven observers for each experimental condition are shown by the white-bar graphs of Figure 5. Mean fixation duration was about 235 msec for the low conspicuity condition and about 207 msec for the high conspicuity condition. This difference was statistically significantly ($F(1,6)=31$, $p=0.001$). Mean fixation durations for the 10°, 20°, and 40° IFOVs were 232, 218, and 212 msec, respectively. The decrease in fixation duration with IFOV was not statistically significant ($F(2,12)=3.6$, $p=0.08$).
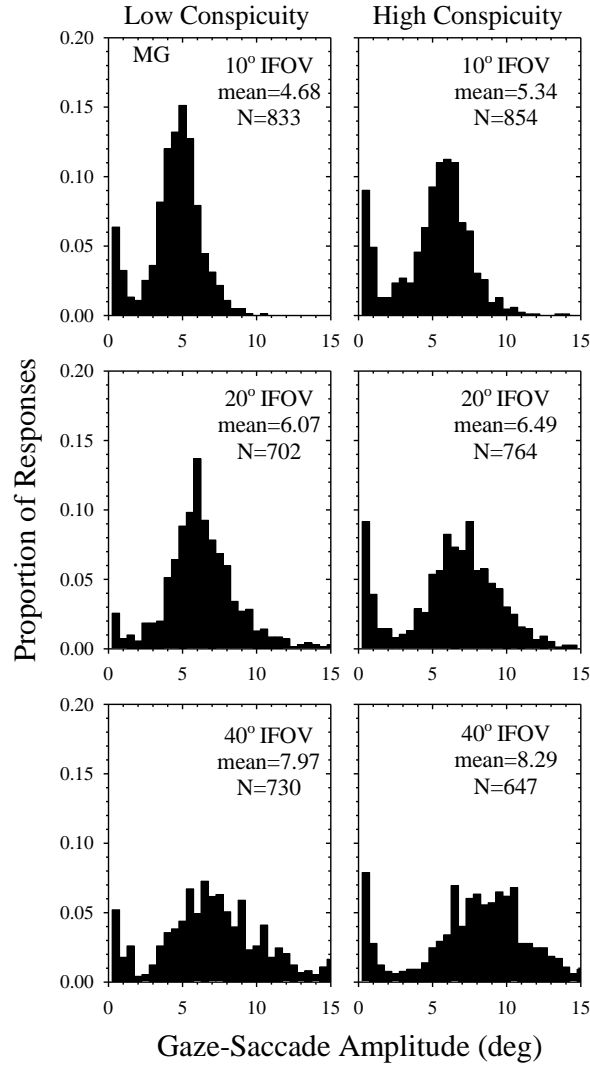
Fig. 4.   Gaze-saccade amplitude histograms for observer MG obtained for both levels of target conspicuity and all three IFOVs. Mean amplitude decreases and the distributions become generally flatter as IFOV and target conspicuity increase.

D. Gaze Saccade Amplitude-Duration Main Sequence

The relationship between gaze-saccade amplitude and duration for one observer under the 40° IFOV condition is shown in Figure 6 for the low-conspicuity condition and in Figure 7 for the high-conspicuity condition. The data of both figures were fitted with the power function of Eqn. (1). The best-fit parameter values and associated R^2 values for power-function fits to data analogous to those of Figure 6 and 7 but for all observers and all experimental conditions are shown in Table 1. For the scaling parameter, a, the main effects of conspicuity and IFOV both approached statistical significance [$F(1,6)=5.4$, $p=0.06$ and $F(2,12)=3.21$, $p=0.08$, respectively]. For the exponent, b, the main effect of conspicuity was statistically significant [$F(1,6)=15.9$, $p=0.007$)], but that of IFOV was not [$F(2,12)=0.213$, $p=0.81$].
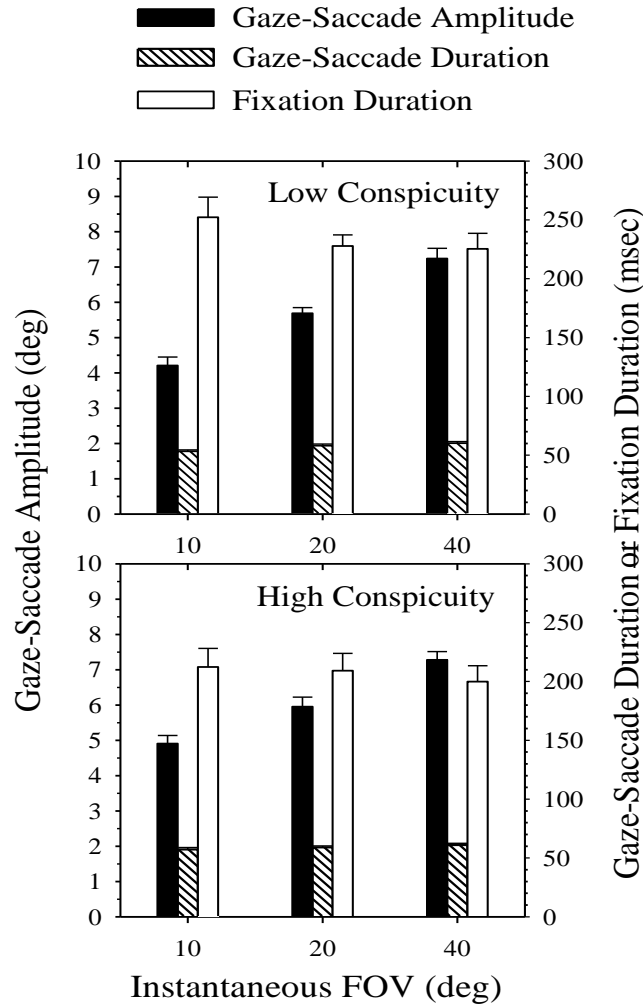
Fig. 5. Gaze-saccade amplitude, gaze-saccade duration, and fixation duration averaged over all seven observers for both levels of target conspicuity and all three IFOVs. All three measures varied significantly with target conspicuity, but only gaze-saccade amplitude varied significantly with IFOV.
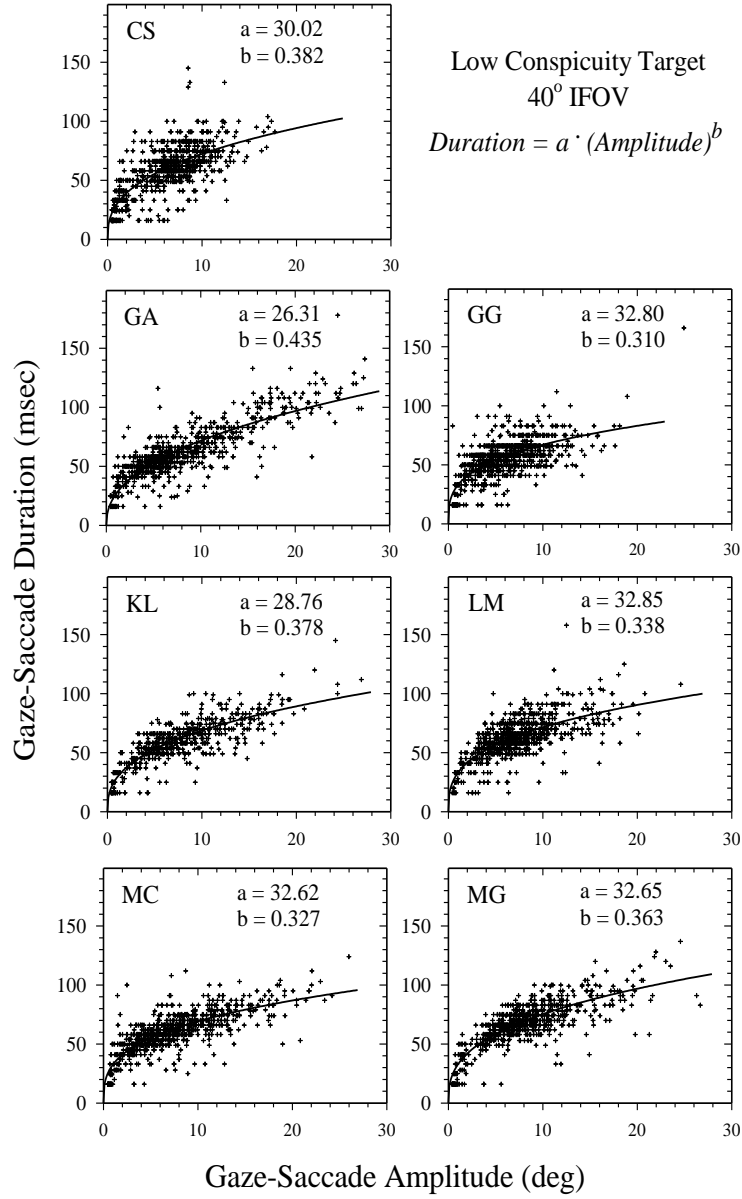
Fig. 6. Gaze-saccade amplitude-duration plots for each observer obtained for the Low-Conspicuity/40°-IFOV condition.

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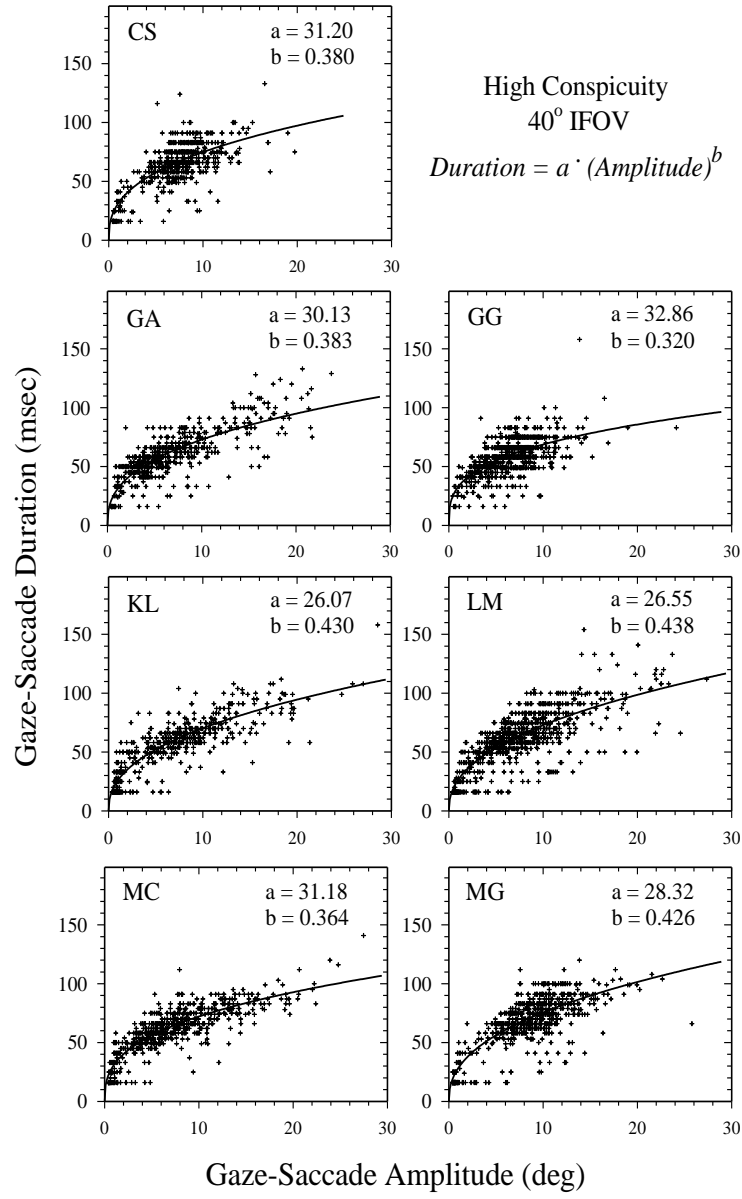
Fig. 7. Gaze-saccade amplitude-duration plots for each observer obtained for the high-conspicuity/40°-IFOV condition.

Table 2. Mean Scaling Parameters (*a*), Exponents (*b*), and R^2-values Obtained from Fitting Eq. (1) to the Data of the Seven Observers.

IFOV	Conspicuity		Mean	s.e.m.
10°	low	*a*	33.62	0.989
		b	0.339	0.024
		R^2	0.400	0.086
	high	*a*	31.57	1.612
		b	0.397	0.031
		R^2	0.505	0.144
20°	low	*a*	32.04	0.795
		b	0.362	0.014
		R^2	0.522	0.106
	high	*a*	30.20	0.929
		b	0.398	0.019
		R^2	0.565	0.126
40°	low	*a*	30.86	0.974
		b	0.362	0.015
		R^2	0.656	0.102
	high	*a*	29.37	0.896
		b	0.393	0.015
		R^2	0.592	0.123

4. DISCUSSION

A. Head, Eye, and Gaze Movements

There is both theoretical and experimental evidence that, for randomly distributed targets, systematic search is more efficient than random search [11,25,37,38,39,40]. This is of particular interest because the present observers all adopted a systematic search strategy even though they were given no instructions as to how to perform the FVS task [43]. Similar findings have been reported for other FVS, and related, tasks [25,39,51,52]. In those previous studies, there was significant interobserver variability in the search patterns but most displayed a clear directionality which was evident even when possible target positions were irregularly distributed and were known to the observer [53,54]. Gilchrist & Harvey [54] interpret this finding as evidence of a cognitive influence on the scanning pattern. Additional evidence for higher-level influences on scanning patterns and gaze-saccades will be discussed in Section F.

B. Gaze-Saccade Amplitude and Duration

The gaze-saccade amplitudes summarized in Figure 5 are generally similar to those found in the few previous studies of FVS in which this variable was measured. In the case of a simulated surveillance task [10], mean gaze-saccadic amplitude was estimated to be about 8.6°. For search tasks involving random-dot backgrounds [17], a single cartoon icon among many [18], and an assortment of real-world images [23], mean gaze-saccadic amplitude was found to be about 7°, 5.5°, and 5°, respectively. Gaze-saccade amplitude and duration are highly correlated, and so the latter is often not assessed in the context of visual search. In fact, this

variable was not assessed in the four FVS studies identified above. The relationship between gaze-saccade amplitude and duration, as well as their relationship with target conspicuity and IFOV will be discussed further in Sections D-F.

C. Fixation Duration

It has been well documented that little or no visual information is obtained during the saccadic eye movements that accompany visual search (see [55]). Thus, the amount of information extracted from a visual scene during a given sequence of saccades is primarily dependent on the length of time that each scene location is fixated. The present FVS task involved simple target detection, and could presumably be performed with a minimal fixation duration. The mean fixation duration found here for observers performing FVS was about 221 msec. The mean fixation durations reported in other studies using search tasks in which the target was not initially visible and could have appeared anywhere in the visual field were: 280 msec [10], 360 msec [12], 350 msec [13], 250 msec [14], 210 msec [18], and 460 msec [17]. As would be expected, fixation duration is affected by the nature of the search task and the characteristics of the test stimuli used [56].

When performing visual search using multiple fixations, each fixation must provide information concerning both the foveal and peripheral visual field [4,23]. In most visual search tasks, the foveal information is required to determine if the target is present, and the peripheral information is required to identify the next location to be fixated [57]. In FVS, however, the peripheral information resides only in the background image. Therefore, in the present FVS task, in which background detail was relatively homogeneous, it might be expected that the visual processing that takes place during fixation, and that determines the length of fixation, will be inversely related to the conspicuity of the target. The increase in fixation duration with decreasing target conspicuity, shown in the data of Figure 5, is consistent with this expectation.

D. Amplitude-Duration Main Sequence

It has been shown that the relationship between saccadic amplitude and duration (i.e., one of the "main sequence" relationships [58]) can convey useful information in a number of experimental contexts including saccadic modeling [32,59,60], clinical disorders [61], comparisons among species [62], and other physiological movement systems [63-66]. In the context of visual search, saccadic amplitude and duration are clearly dependent on the task and the stimuli used to elicit them. For instance, it is difficult to compare FVS data with search data obtained using discrete, identifiable search locations (e.g., [9,67-69]) because the arbitrarily chosen distances among the latter may affect saccadic characteristics. Thus, one potential advantage of main sequence data is that the parameters may provide a scale-independent metric for comparing saccadic responses.

There is some ambiguity in the literature, however, concerning the specific functional relationship between saccadic amplitude and duration. Bahill *et al*. [58] describe their log saccadic-amplitude vs. log saccadic-duration data as nonlinear over a three log unit range of saccadic amplitudes (from about 0.5°–50°). However, given the relatively large spread in those data for magnitudes less than about 1°, it appears that a linear function would fit the data as well as any other over the range 0.5°–10°. Those data are plotted on log-log coordinates suggesting that saccadic duration and magnitude are related by a power function. Further, Becker [70] has reviewed much of the relevant data and concluded that a power function provides an acceptable fit to saccadic amplitude vs. saccadic duration data for magnitudes between about 0.5° and 5.0°.

Further, he contends that the power exponent over this data range is about 0.15–0.20, and he also plots data from other studies and shows that they are well fit by a linear function for saccadic magnitudes from about 5º to 50º. Becker [70] notes that there are significant deviations from the linear function for saccadic magnitudes below 5º, although these deviations are not evident in the data he presents. Baloh *et al*. [71] present evidence that amplitude-duration functions are linear over a range of 6º–90º, although they note that some observers' data show a "mild curvature". Finally, Van Gisbergen *et al*. [72] have concluded that a linear function is sufficient for fitting amplitude-duration data over an amplitude range of about 5º–30º. Thus, although there is some justification for fitting piecewise linear functions to the full range of amplitude-duration data, there does not appear to be a theoretical or practical reason to do so for the data of the present study. We have, therefore, fitted the two-parameter power function of Eqn. (1) to the present data that extends over an amplitude range of about 0.5º–28º.

The parameter values obtained by fitting Eq. (1) to the present data are shown in Table 1. Neither the scaling parameter, *a*, nor the power-exponent, *b*, varied significantly with IFOV, and so only their variation with conspicuity will be discussed here. Main sequence data comparable to those of Table 1 are not available from previous studies of FVS, but they are available for other saccadic responses. Shown in Table 2 are parameter and R^2 values obtained by fitting Eq. (1) to data obtained from twelve studies that report saccadic amplitude-duration data [73]. The data of Table 2 fall into two general groups corresponding to scaling factors and exponents of about 22 and 0.4 [29,44,58,71,74-76], and 10 and 0.7 [2,27,59,77,78]. The studies listed in Table 2 represent a variety of visual tasks, but one factor that appears to distinguish the two groups is that the target stimuli, or their possible locations, were continuously visible in only the second group described above. Although other factors may affect the main-sequence relationship, we will denote this as the *continuous* group. In the other group, denoted the *flashed* group, targets (and/or target locations) were only intermittently visible.

Shown in Figure 8a are amplitude-duration functions obtained from the mean *a* and *b* parameter-values for the *continuous* group, the *flashed* group, and the present study. The segregation of parameter values for the *continuous* and *flashed* groups is more clearly shown in Figure 8b, where the data also indicate that parameter *a* varies about equally for the two groups whereas parameter *b* varies more for the *continuous* group. The higher exponent of the *continuous* group is associated with a lower scaling parameter. As a result, the two functions intersect at a gaze-saccade amplitude of about 15°, although the curve fitting procedure clearly distinguishes the groups. Also plotted in Figure 8b are the parameter values (triangle and square) obtained from the two target conspicuity conditions of the present study. These values appear to be segregated from those of the other studies, indicating that main-sequence data can be used to distinguish among this set of visual tasks.

Another indication of the potential utility of the main-sequence relationship is shown in Figs. 8c and 8d. In these figures, the parameter values are plotted as a function of mean gaze-saccade amplitude. There is a clear segregation by the parameters a and b despite the fact that saccadic amplitude differs both between and within the continuous and flashed groups. Further, only three of the functions show a variation with gaze-saccade amplitude. Thus, the main-sequence data allow a scale-independent comparison between the continuous and flashed groups, as well as, to a lesser extent, between those groups and the present FVS data. However, there is insufficient data in the literature to determine whether these, or other, aspects of main- sequence data can consistently discriminate either among FVS tasks or between FVS tasks and tasks

Table 2. **Results of Fitting Eq. (1) to Amplitude-Duration Data Obtained From Previous Studies.**

Study	Parameters (a, b, R2)	Notes	Data Evaluated
Bahill, *et al.* (1975)	21.7, 0.362, 0.932	[3,5]	Range: 0.04°-53°; Fig. 2
Baloh, *et al.* (1975)	23.2, 0.445, 0.944	--	Range: 2.7°-36°; mean of Figs. 3a-c
Eizenman *et al.* (1984)	25.1, 0.340, 0.901	[3]	Range: 0.5°-19°; Fig. 10-89 (primary saccades only)
Hallett (1978)	22.2, 0.400, 0.975	--	Range: 0.25°-13°; mean of Figs. 5, 7, & 12 (normal only)
Krafczyk, *et al.* (1992)	25.2, 0.406, 0.600	[2]	Range: 5.9°-28°; Fig. 73-2A (ipsiversive)
Lebedev, *et al.* (1996)	16.8, 0.546, 0.970	[4]	Range: 0.13°-30°; Fig. 2a
Yarbus (1967)	20.3, 0.386, 0.918	--	Range: 0.33°-18°; Fig. 73, mean of two *O*s
Becker & Fuchs (1969)	5.27, 0.881, 0.999	[1]	Range: 6.9°-63°; Fig. 1a, illuminated
Collewijn, *et al.* (1988)	9.78, 0.712, 0.984	[1]	Range: 2.6°-50°; Fig. 5
Epelboim, *et al.* (1997)	13.4, 0.566, 0.920	[1,2]	Range: 5°-44°; Fig. 5, looking-only, mean of four *O*s
Inchingolo & Spanio (1985)	10.4, 0.685, 0.929	[5]	Range: 5.2°-70°; Fig. 2a
Robinson (1964)	10.4, 0.642, 0.985	[1,5]	Range: 5.1°-40°; Fig. 3, temporal & nasal

[1]—Target and/or target locations continuously visible
[2]—Head free
[3]—Data, as analyzed here, may be under sampled due to overlap of plotted data points
[4]—Parameters obtained from original paper
[5]—Method or task not fully described

employing other stimuli and search methodology.

E. The Useful Visual Field in FVS

The human visual system is spatially non-uniform with more highly detailed vision localized near the fovea. This characteristic limits the useful field-of-view, from which an observer can obtain information during a single fixation. The general concept of a useful visual field has been studied in several experimental contexts and has been variously referred to as visual lobe [38], visual span [67], perceptual span [9,79], and functional visual field [80].

There are two aspects of the present data which may indicate the size of the useful visual field associated with the present FVS task. The first is the increase in gaze-saccade amplitude as IFOV is increased (see Figure 5) [81]. The mean gaze-saccade amplitude for the IFOV-10° condition is about 4.7°. This is very close to the radius of the IFOV, and therefore it cannot be determined whether the measured amplitude is due to the limited IFOV size or to properties of the eye-movement control system. For the IFOV-20° and IFOV-40° conditions, gaze-saccade amplitudes are larger than for the IFOV-10° condition but are less than the radii of their corresponding IFOVs. Thus, when allowed to do so, the observers made gaze-saccades of about 6°-7°, which may be taken as the radius of the useful visual field for the present FVS task.

The second aspect of the present data from which the size of the useful visual field can be inferred is the spatial separation of individual gaze scans shown in Figure 2. For the five observers who showed regular scanning patterns, the mean interscan distance was about 8°. This

value is similar to the size of the useful visual field estimated from the gaze-saccade amplitude data. Given that there are no consistent features 6°-8° in size in the background images, these gaze amplitudes are apparently determined by higher-level processes that assess the visibility of the potential target and determine the minimum size of the retinal area, centered on the fovea, that will be necessary to detect it.

F. Higher-Level Influences on Gaze-Saccade Characteristics

Models of saccadic eye movements have been proposed, for the most part, to describe responses to step displacements of simple stimuli [29,70,72,74,82]. A common feature of these models is a mechanism for detecting and reducing the retinal distance between the fovea and the target to be fixated. Consistent saccadic responses are also possible, however, when there is no explicit target and thus no positional error to minimize [27-29,32]. Because the gaze saccades described here were made with no target visible, we assume that their characteristics were determined by higher-level processes. The effects of higher-level processes have been explicitly considered in the study of eye-movements (e.g., [2,32,67,83,84], visual search [4,9,49,85], visual attention [19,86,87], and reading [68,88,89]. Data obtained when saccades are determined by higher-level processes may be of both theoretical and practical interest in that those saccades have been found to differ quantitatively from saccades determined by retinal stimulation. For instance, higher-level saccades tend to have lower peak velocities, lower saccadic gains, smaller amplitudes, and longer latencies than saccades made to retinal stimuli [29,33,90]. These differences indicate that a retinal target is required to produce the fastest saccades, and that generally slower (although not necessarily less optimal) saccades result from the introduction of higher-level influences such as inhibitory, attentional, or memory processes [33,91,92]. The sudden appearance of a target light is usually a very salient visual stimulus. Thus, in the context of the data of Figure 8a, it might be expected that faster saccades would be found for the flashed group than for the continuous group. However, for saccadic amplitudes less than about 15°, saccadic duration is greater (i.e., saccadic velocity is less) for the flashed group. Retinal targets were available in both groups, but possible target locations were known to the observers only in the continuous group. It is known that directing spatial attention alone (i.e., without a concomitant eye movement) to possible target locations can facilitate motor performance [93,94], and spatial representations that could subserve shifts in spatial attention are known to exist at several levels of the visual-motor system which are implicated in eye-movement control [32,85,95]. The convergence and eventual crossing of the continuous and flashed functions of Figure 8a further suggests that the higher-level, attentional facilitation mentioned above decreases for more peripheral target locations, and may be exceeded by other factors (e.g., retinal target saliency) beyond about 15°.

An amplitude-duration function obtained from the mean gaze-saccade data of the present study is also shown in Figure 8a. This function is similar in form to that of the *flashed* group, but it is shifted upward on the duration axis, again indicating a lower saccadic velocity for a given saccadic amplitude. The neural activity directly responsible for saccadic eye movements emanates from what are known as burst neurons located in the brain stem reticular formation (see [32]). However, various hierarchically organized and interrelated cortical and sub-cortical areas are known to both directly and indirectly affect the output of the burst neurons [32,96-98]. The present data and those of the *flashed* group appear to be more similar than are the data of the *continuous* group to either the present data or the *flashed* data. It is not known how main-sequence parameters may be affected by the contribution of various neural mechanisms, but the

data of Figure 8a suggest that higher-level processes can affect either one or both parameters depending on the tasks and stimuli used.
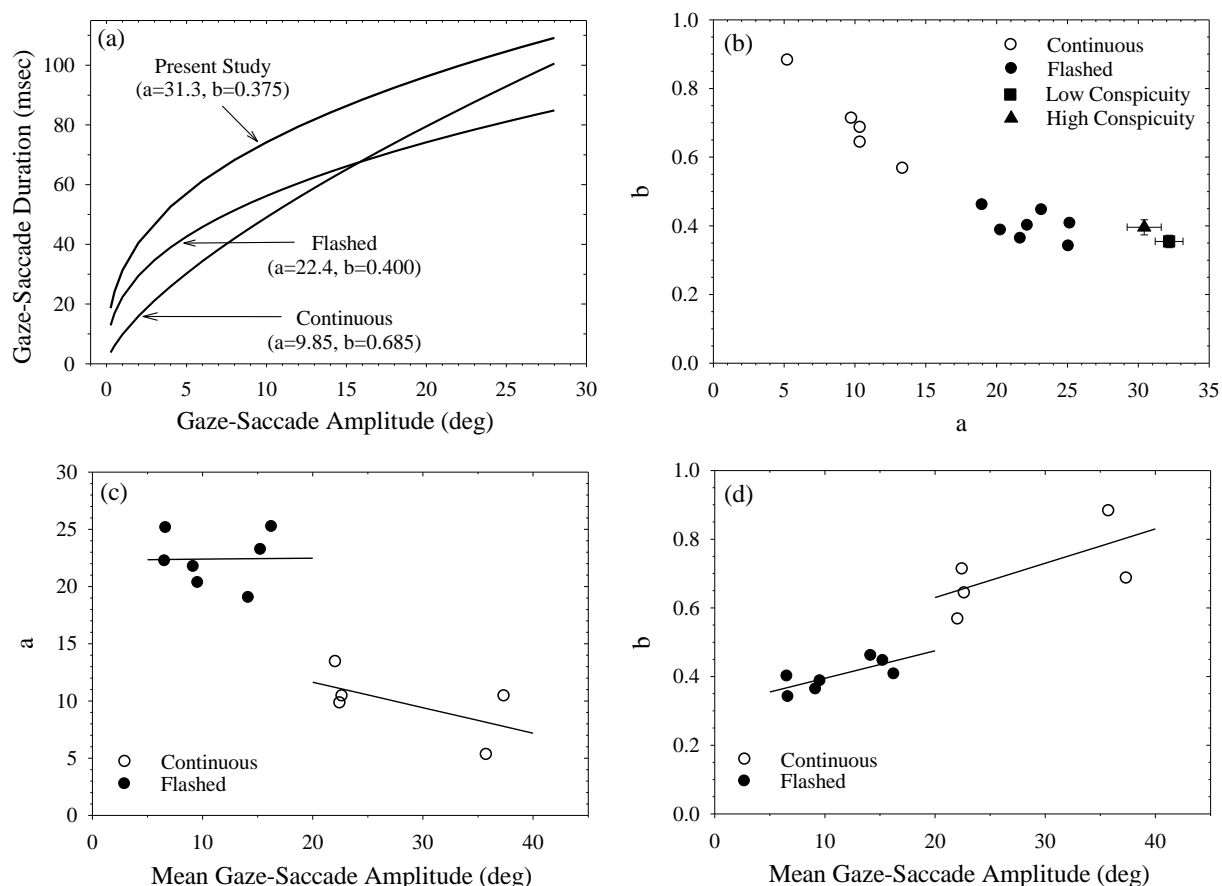

Fig. 8. A comparison of the present data with data obtained from previous studies that have been classified here as either *flashed* or *continuous*. (a) amplitude-duration main sequence functions, (b) scatter plots of the power parameter, *b*, and the scaling parameter, *a*, (c) scaling parameter as a function of mean gaze-saccade amplitude, and (d) power parameter as a function of mean gaze-saccade amplitude.

5. CONCLUSIONS AND IMPLICATIONS FOR REAL-WORLD SEARCH

When presented with a FVS task, the present observers all adopted a systematic search strategy that is known to optimize search efficiency. The gaze-saccade amplitude and gaze duration associated with FVS increased, and fixation duration decreased, with increases in target conspicuity. However, only gaze amplitude varied significantly with IFOV. These findings are generally consistent with those reported for laboratory search tasks in which possible target locations were known to the observers.

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The amplitude-duration main sequence functions obtained from the literature and summarized here differed depending on whether the search target, or possible target locations, where visible. Both of those sets of functions differed from the data obtained here for the FVS task. The main difference was a higher scaling factor for the best-fitting power function associated with the present data, which indicated that gaze-saccade durations were greater for a given gaze-saccade amplitude.

Gaze-saccade amplitude asymptoted at about 6°-7° as IFOV was increased from 10° to 40°. Further, the mean distance between individual scan lines in the FVS search patterns was about 8°. These two aspects of the present data indicate the size of the useful visual field associated with the present FVS task is about 6°-8°.

Targets were not visible during the present FVS task, and it is therefore postulated that the observed gaze-saccade characteristics were determined primarily by neural processes above the retinal level. This finding may be of particular relevance to the analysis of operational tasks such as air-to-ground target acquisition, monitoring radar displays, and search-and-rescue, since such tasks involve search behavior that is dependent on the observers' knowledge of target properties and environmental conditions, whether or not the target is visible. In addition, the extent to which gaze behavior is dependent on higher-level or cognitive functions may determine the degree to which these tasks can be trained, and may suggest criteria for designing the most effective training methods.

ACKNOWLEDGEMENTS

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